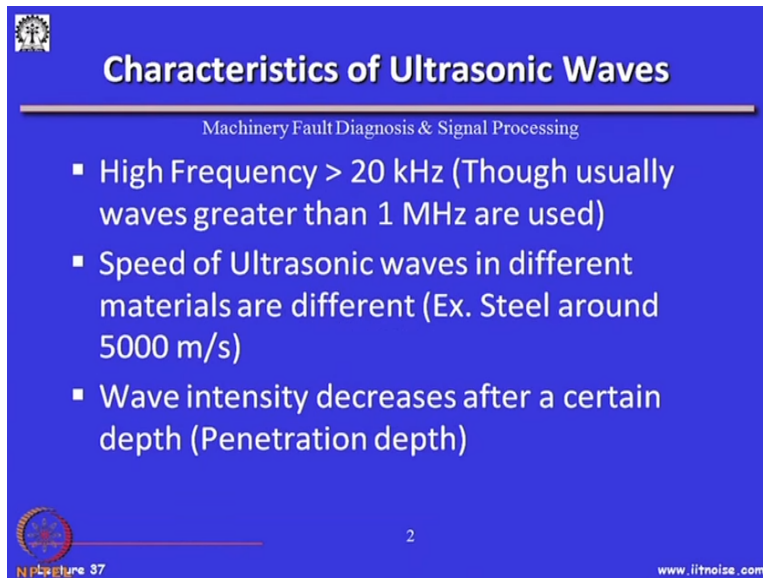


Machinery fault diagnosis and signal processing
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Indian Institute of Technology – Kharagpur

Module No # 08
Lecture No # 37
Ultrasonics

This lecture is an ultrasonic which is another technic of NDT which is predominantly used in condition based maintenance as a non-destructive technique to evaluate the effectiveness of for example welding, detection of cracks and so on. So we will look into the principles behind this ultrasonic this class few applications and recent development in ultrasonic that is the phased a technology which is used in getting an over idea while doing an ultrasonic scanning on an equipment okay.

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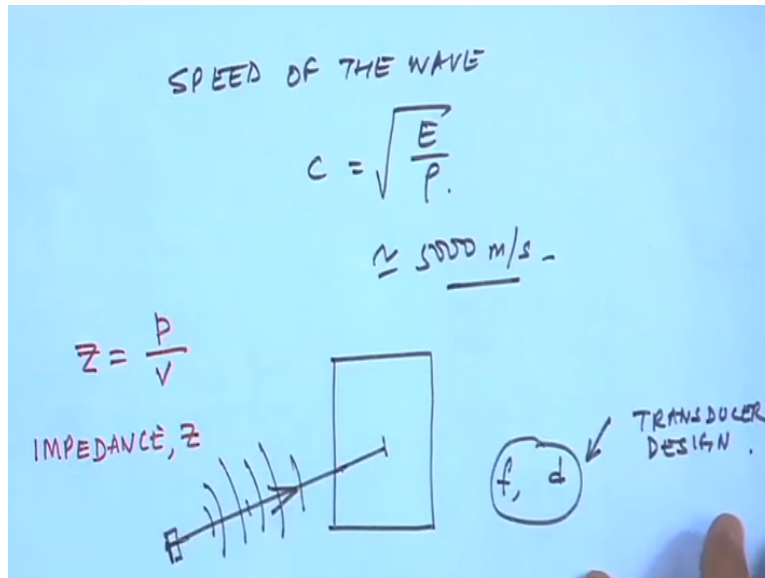
The slide is titled "Characteristics of Ultrasonic Waves" and is part of a presentation on "Machinery Fault Diagnosis & Signal Processing". It lists three key characteristics of ultrasonic waves:

- High Frequency > 20 kHz (Though usually waves greater than 1 MHz are used)
- Speed of Ultrasonic waves in different materials are different (Ex. Steel around 5000 m/s)
- Wave intensity decreases after a certain depth (Penetration depth)

The slide includes a small logo in the top left corner, a circular logo in the bottom left corner, and the text "NPTELecture 37" and "www.iitnoise.com" in the bottom left and right corners respectively. The number "2" is centered at the bottom.

So essentially ultrasonic waves are sound waves and these waves are as you defined ultrasonic any wave above 20 kilo hertz though in the case of ultrasonic which are used in fault detection we use signals higher to frequencies of 1 megahertz and so on. These waves are very directional and then they can propagate in media and so on and we will see how these the propagation in the medium is effected if there is a defect and then how we can identify those defects.

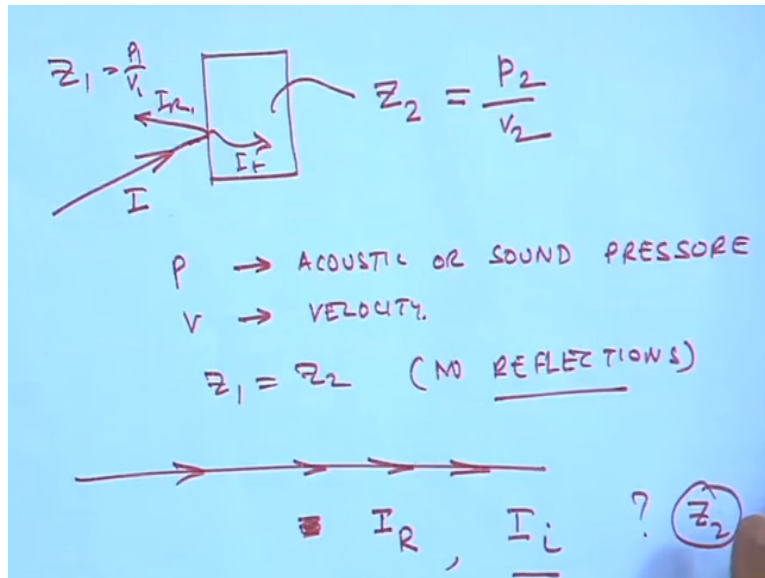
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Ultra sonic waves another important principle of ultrasonic wave is the speed of the wave is dependent on the material property okay for example okay for example in steel the speed of sound is about 5000 meter per second. So one needs to know the different speed of ultrasonic sound waves in a material and then this wave once it is incident we will look into the suppose is an ultrasonic wave front going in this direction and there is a certain depth to which it can go that depends on the power of the ultrasonic wave that depends in the frequency of wave and the diameter of the wave and so on.

So that is what it is used in the transducer design so essentially in ultrasonic we send a wave and depending on the impedance another important concept which I am going to introduce in a post exists what is known as the impedance so Z is the okay.

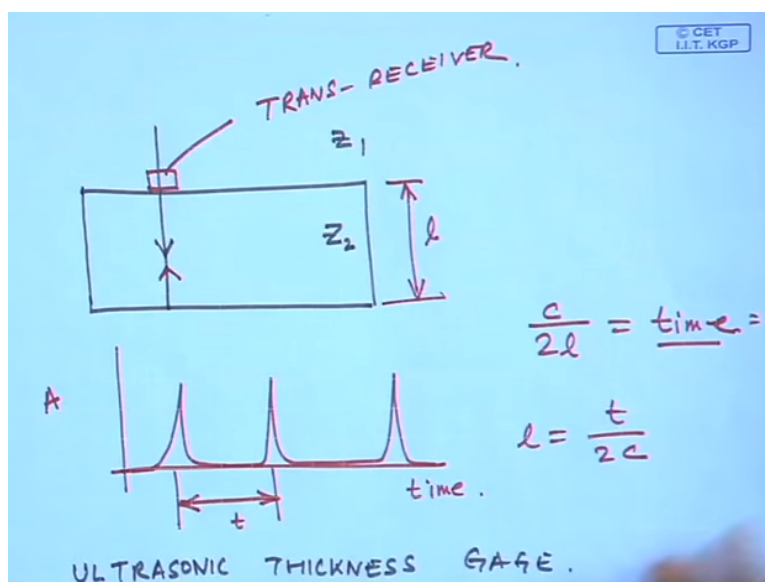
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For example I have medium certain impedance is that to which is P_2 / V_2 and the impedance of this medium which is Z_1 is that which is P_1 / V_1 where P is the acoustic or sound pressure V is the velocity okay. So depending on the relationship between Z_1 and Z_2 some will be incident some will be transmitted some will be reflected and so on okay. So the impedance of the material if $Z_1 = Z_2$ the wave would get transmitted without any no reflections.

So this is the physical principle of the physics behind such sound waves so depending on the intensity of Z_2 sorry the reflected wave intensity and the incident wave intensity we can find out some clue what is the Z_2 of the material.

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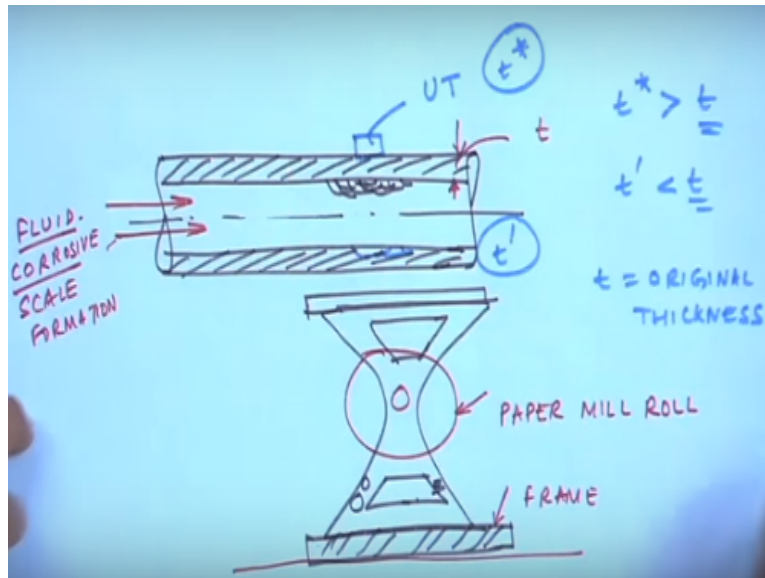
Now if there is a difference in the impedance this reflection coefficient which is $R = I_R / I_I$ will be dependent okay they will vary. I think but a function of Z_1 , Z_2 and from acoustics you can find out what is the relation between reflection coefficient between the transmission coefficient and so on. Now if there is a defect in the material say in the form a crack or void defect in the form of crack or void in a material.

This wave front is going to get reflected sorry Z_1 , Z_2 some new Z star now if I move this is a probe. If I move this probe along the surface of the body and then this incident wave is set there is instances when the intensity of the reflected wave will be different then the intensity at this location say for example R star at another location it will be may be R . So by knowing the difference of this intensity we can get some clue as to what is wrong in the material and so on.

So this is how the ultrasonic wave are used to find out the presence of the defect which in effect because of the change in impedance. Another we use we make of ultrasonic wave is if you look at the wave is a material and we send an ultrasonic wave this is Z_2 this is Z_1 . Because it is twice impedance discontinuous boundary there will be reflections and this can be a trans-receiver. Say if I move this probe all throughout I can do couple of things first is with time I can see some ultrasonic wave intensity okay.

So this time period is nothing but responsible for this is L the thickness of the material so the time period will be $C / 2L$ will be this time okay. T so indirectly if I know the time period between such intervals where i sent the wave and get the reflected wave and if the speed of sound is known I can find out L as to $IC / 2C$ and this is the principle behind what is known as ultrasonic thickness gage this has lot of industrial applications.

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For example in a pipeline has certain wall thickness this is the pipeline and this is to have a certain thickness say T is its thickness. Now this could be carrying some fluids in the plant could be some fluid which could be corrosive or otherwise there could be scale formation because of impurities so what would happen over the either material would get deposited or material would be depleted because of corrosion.

So from the outside if I put such ultrasonic probes which I am writing as UT so and then try to measure the new thickness T^* or T' . So these thicknesses will be in one case T^* is greater than T in another case T' is less than T where T is my original thickness okay. So this kind of probes are used for measuring the thicknesses of pipes in chemical plant, process plant over the years you could not know from the outside whether the pipe is having certain deposits in forms of scale or pipe as for corroded to a certain thickness.

So if you do a regular scanning by a ultrasonic probe along the length of the pipe you can see whether the thickness variations are there is one applications. Another application is many a times you know we have been plants you know any vary in you know I I know a case of a paper mill wherein this the owners of the paper mill actually bought a paper mill the whole plant okay out of the eastern Europe from Romania shipped them to India and installed it in a location in India.

And they started producing papers the plant was in place but they were never sure as to what is the dimensions because they never had any drawings of this sections of the critical sections of the plant machinery. For example in a paper mill maybe in the some of my earlier classes are shown in the figures of this paper with lot of rolls and actually this rolls are held on frames you know this sort of things cross sections.

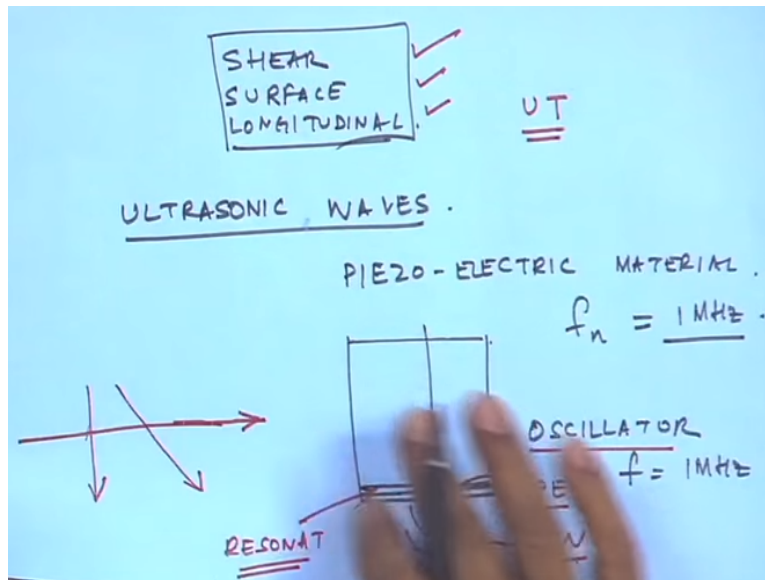
These are bolted to the foundations I am just doing one of the front views but nobody knows you know there are series of such frames in a put in a plant where the paper will roll and this is the frame which is of course put in a foundation on a shaft roll. So in such a plant there were cases where the thickness of this though they knew this was steel but nobody knew what was the thickness of this material.

So in such a scenario we used to put ultrasonic probes and then we are able to measure the thickness and then we could reconstruct the entire plant machinery drawings in terms of once we know the thickness wont be measure that their dimensions. So what I mean to say is a lot of unknown thicknesses can be measured using ultrasonic probes because you have access from the outside and then you can know the thicknesses from the appropriate places this is one area where ultrasonic is used.

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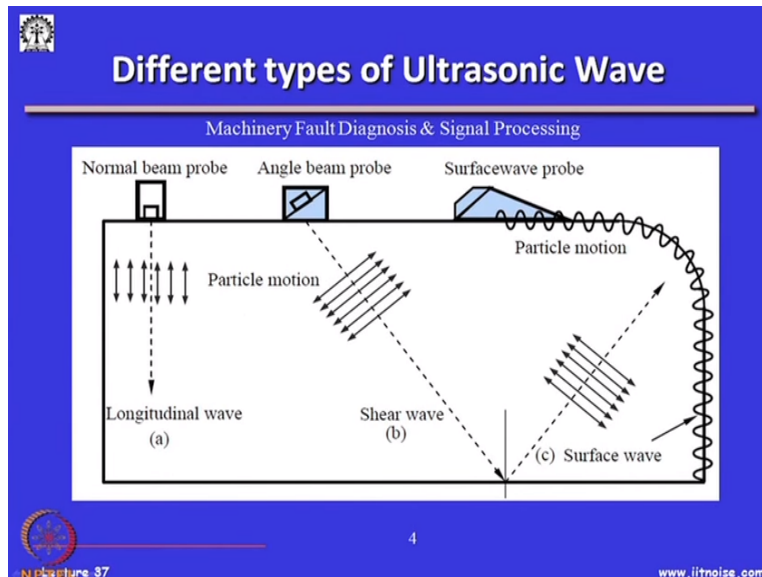


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Now this waves you know I have not told you about the type of wave you know what is the type of wave as you know this are all sound waves and sound wave and structures can propagate as you know Shear wave or surface wave okay and sometimes as longitudinal wave and speed of propagation of these waves are different and if you look into any book on acoustics they will give you the equations of this waves which are propagating in solids, fluids and depending on the type of weight the speed of sound in this particular are different.

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And we will show you one general case for example this is the view wherein this is the body so if have a normal brain probe and this actually is perpendicular to this structure and A is actually a longitudinal wave okay. Now if I move it along this probe at an angle, this angle could be 45

degree, 60 degree, 70 degree is going to produce a shear and this shear wave is going to get reflected okay out of this area because this continuity and then we can see if there was a defect in the path there will be reflection at a different angle okay.

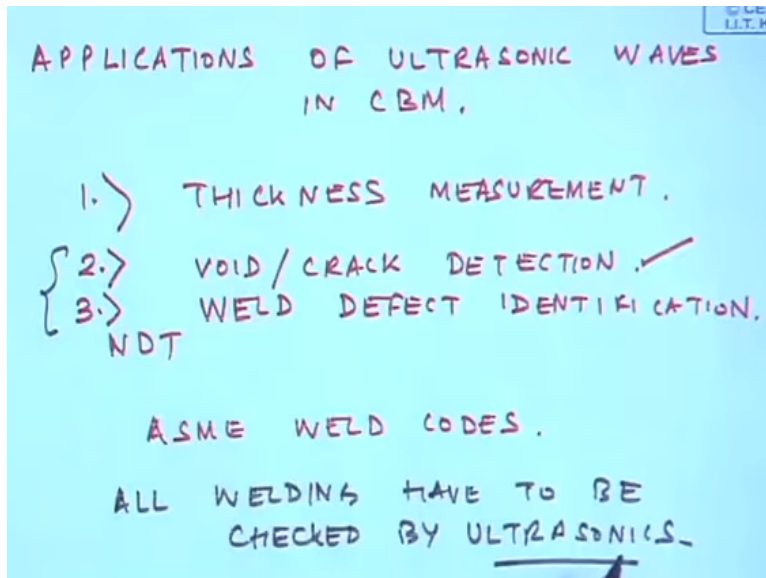
So this kind of waves can be produced by having an angle B otherwise or we can reduce a angle like a total internal reflection and then this will almost on the surface. So we can generate surface waves so and these are generated by this ultrasonic probes okay. So what is the this ultrasonic probe what generates ultrasonic waves how do we physically generate waves essentially what happens there are in a transducer we have certain piezoelectric material and if a small piece of piezoelectric material is held in a casing with a right amount of stiffness okay.

This has a natural frequency F_N this could be equal to maybe 1 megahertz or so very stiff and thin shaft less mass. So will have a very high natural frequency so if I excite this facility crystal by an oscillator where I can generate a forcing frequency is equal to 1 megahertz this is going to resonate and then I will be able to generate a resonant waves. So this is a very simple principle of having a piezoelectric crystal PE crystal which could be made to resonate by a frequency which is equal to resonate frequency and then we can generate such ultrasonic waves.

And this waves if they are normal they will be longitudinal they could be incline they will be shear if I make it more and inclined and finally I can get a surface wave. So this same probe depending on the geometric can be used to produce any of these three types of waves. So one such waves have been generated by an ultrasonic transmitter okay we can now have this wave propagating in a materials and then depending on the impedance of the material because of the defect discontinuity void, crack.

We can get reflected with and depending on the intensity of the reflected wave in comparison with the intensity of the incident wave we can get as to some clue as to what is the change in the impedance and what is the defect and so on.

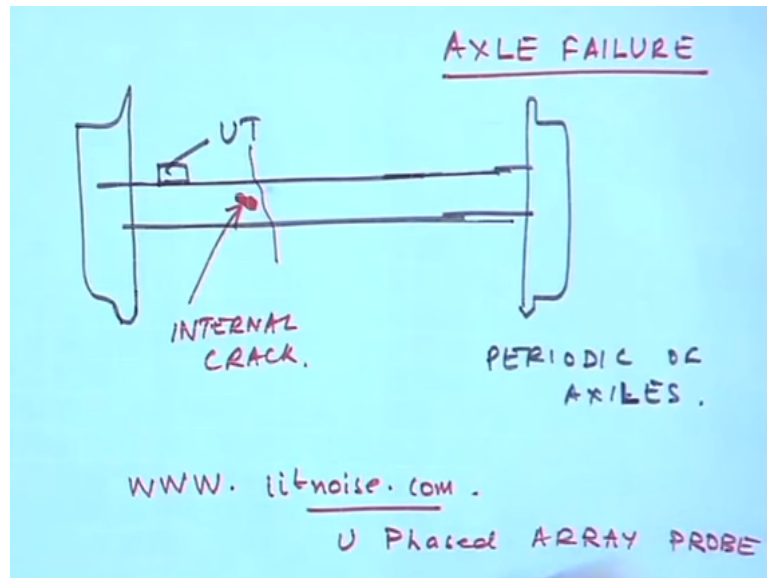
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So ultrasonic application if I was to just briefly write down one of the applications of ultrasonic waves particularly in CBN one of course was the thickness measurement and the other is what is known as the void or crack detection there of course all NDT techniques and this void and crack detection as a lot of engineering application another one specifically for ultrasonic is weld defect identification.

In some critical applications where a welding is done there are many codes like ASME codes ASMI well codes which mandate that all welding have to be checked by ultrasonic okay. So these are the lot of engineering applications. Another applications I will tell you which coming out of Kharaghpur we have a big relay workshop here and I must tell you.

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So if you look at the railway will set because this is the axle the flange and the tread okay. Imagine in a railway axle if there was a crack which was internal which has developed maybe some initiation was there because of weak material or something and over the time this crack has become alarmingly big time will come this crack is so severe that there will be a failure in the axle. Now you can imagine the disastrous consequence of an axle railway axle failure.

So how you detect such internal cracks obviously it is not visible from the outside so what they do in the railway workshop is the they have an UT probe and if you go to workshop you will see the guys will be scanning the entire surface of the axles over a certain period and they have a periodic inspections of the axles okay coming we will come back to example of the welding additional.

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Principle of Ultrasonic Transduction

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- Ultrasonic wave generator (Usually a piezo electric crystal)
- Ultrasonic wave receiver
- Series of ultrasonic waves with a time delay sequence (Phased array technology)



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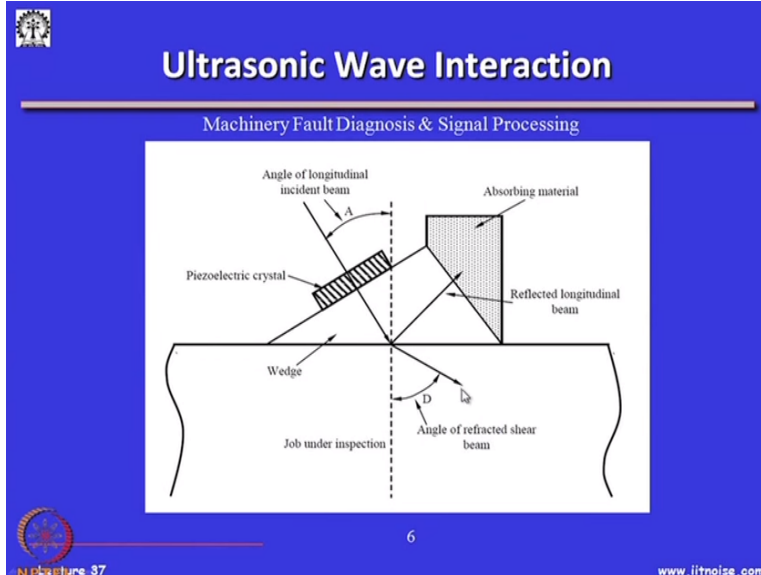
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So the principle of ultrasonic transducer transduction which I just mentioned to you that we have a usual a piezoelectric crystal which is made to resonate at its natural frequency. So this ultrasonic wave is generated and the shape of this ultrasonic transducer enables whether the signal is longitudinal or in the shear mode or it is in the surface and then we also have a receiver and another technique we can generate series of ultrasonic wave and then it in one go I can have a many ultrasonic wave going in as a array and then they get reflected back.

So this helps us quickly find out the defects so this is one of the latest techniques which are they have been using an ultrasonic and we have one such in lab and which you can see in our website www.iitnoise.com. So all these instrumentation are available particularly the ultrasonic phased array probe. I will come to that discussion at the end

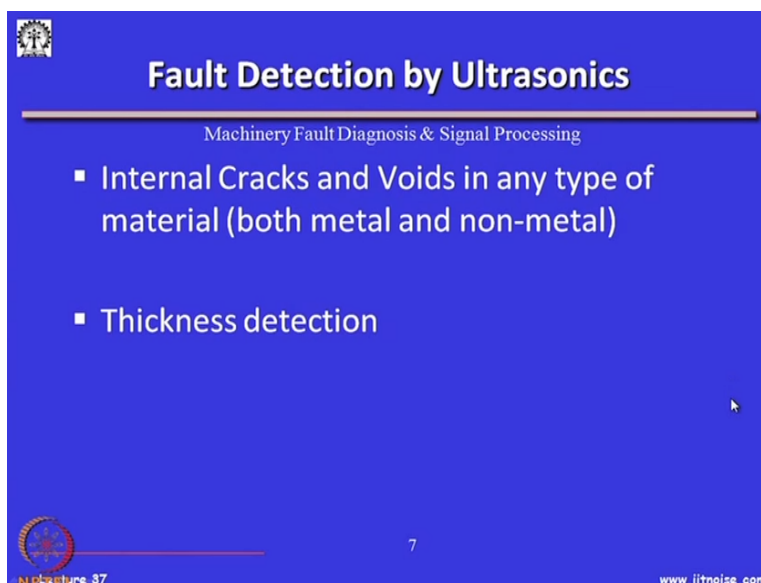
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So if was to explain to you how this ultrasonic wave interacts essentially this is the material this is a material which is being inspected this is a ultrasonic crystal and then this is the incident beam at an angle this beam will get refracted some part of it will get reflected and we have a sound of observing material here sorry absorbing material so that because we do not want any information from here rather we are interested to where this beam gets reflected okay.

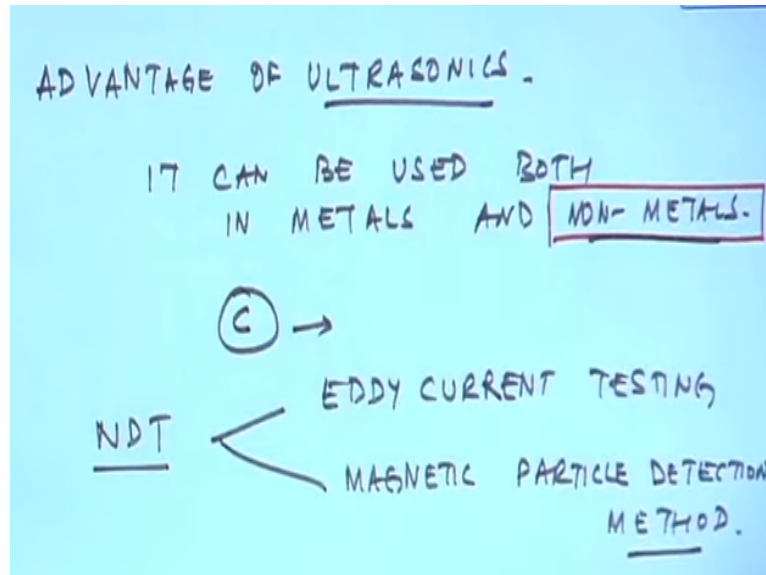
And then looking at this reflected beam we can find out intensity of that where this defect is so on.

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So fault detection by ultrasonic probes one is this signal crack and voids in any types of this materials both metal and non-metal and then is thickness.

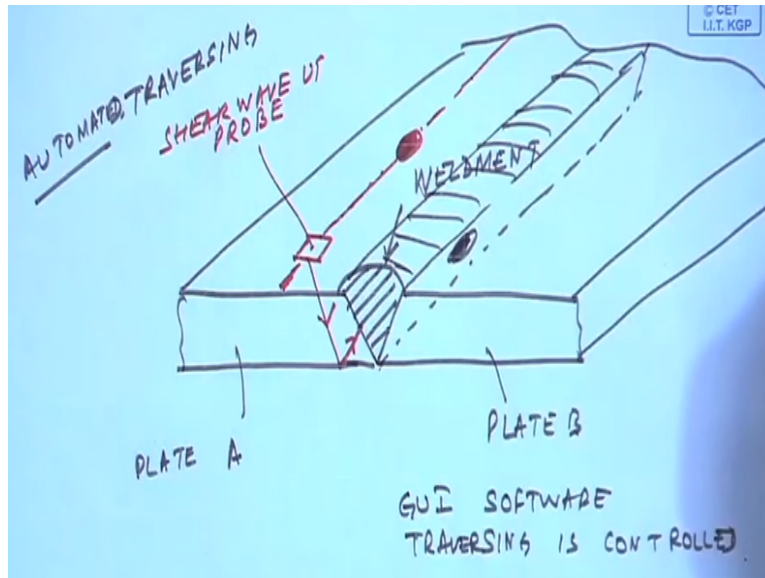
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Another very big advantage of ultrasonic's is it can be used both in metals and non-metals you all many of you familiar the doctors use ultrasound for finding out the ultrasound sonography to find out if something is wrong with you some element is there okay and these are essentially in all elements only thing is that you have to know this speed of sound in that medium unlike in some other entity technique where they have to be metal like the eddy current testing or magnetic particle detection method okay.

They have to be metals but ultrasonic is it can be used in non-metals so this is where it is advantages. Though in many engineering structure we have what we know as the usually made out of steel.

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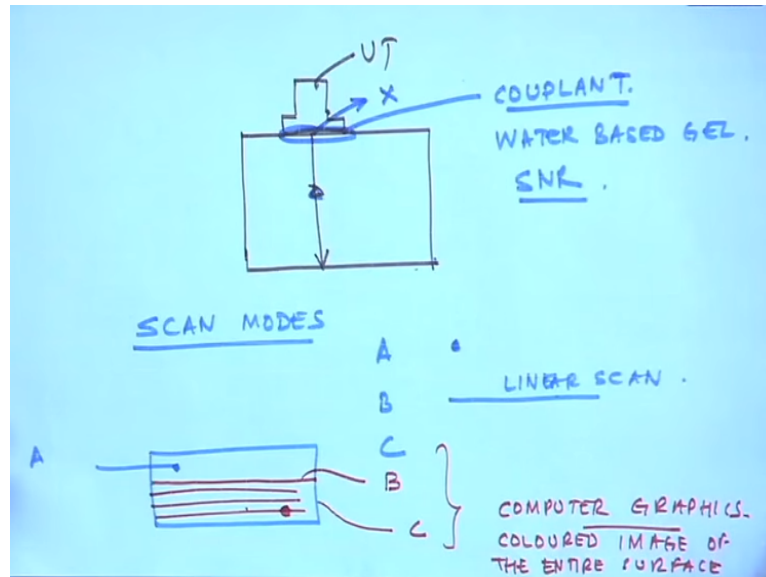
Now I will give you another example how this ultrasonic used for weld flaw detection for example if I have two plates which are but welded so there will be some sort of angle and this two plates are out together. So there will be an weld deposit am showing this weld deposit well element or weld deposit and this is plate A and this is plate B. So what happens is you know if you can think of it this is long plate and then they will be kind of element okay.

So to see if this element as is effective or not what we can do is I can put a sheer wave probe I can put a sheer wave probe UT here wave UT probe. So what it essentially does it sends a beam and then it is gets reflected and this gets into the weldment and I can be traversing this well probe one by one okay along the length of this weldment and whenever there is a flaw in the weldment. If there is a flaw here they intensity of the reflected wave is going to change okay.

So if I get an image of all the intensities of the ultrasonic waves along this line very next to the weldment I can see a high intensity which corresponds to this kind of defects here okay. So that is how the every weldment is checked against any internal well defects this is not possible by a any other techniques this this internal defects are not visible to the ahhh open naked eye. So only thing is that only is that now a days there are many systems wherein this probe is traversing this traversing is automated okay.

And then there are software and then through GUI software where the traversing waves control one can get an image of this length and depending on as many such weldments are there we have the picture of the weldment.

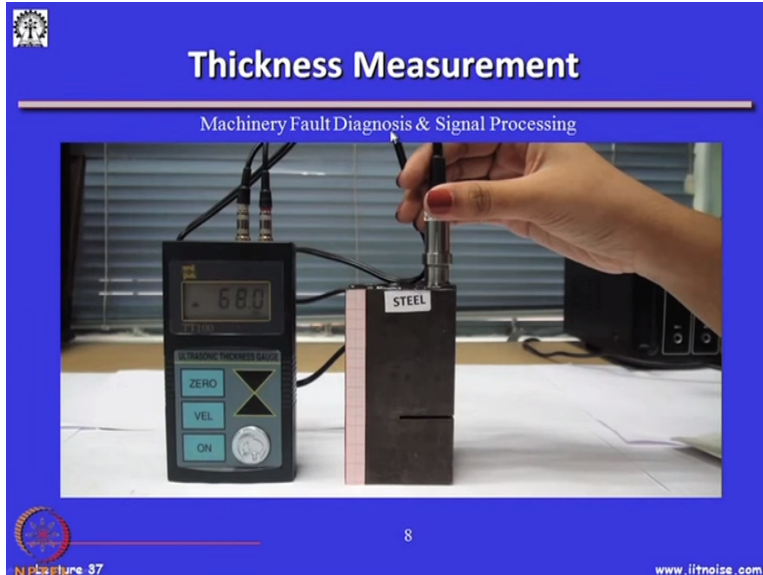
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Another very important aspect while doing such ultrasonic probe is how do we ensure that the ultrasonic wave which we have generated is actually going and then getting reflected and not getting reflected from this surface no reflection. So to ensure this happens usually a couplant is put and this is nothing but a water based gel so that good high signal to noise ratio of the ultrasonic wave is generated.

And so the all the energy ultrasonic wave gets transmitted to the medium so this has to one important thing and this surface for example in this phase of no special treatment of this surface is required. Apart from this layer of couplant is to be put maybe a layer of couplant to be put okay. Now depending upon the nature of this traverse of this image there are certain scan modes in ultrasonic okay will come to this scan mode very soon.

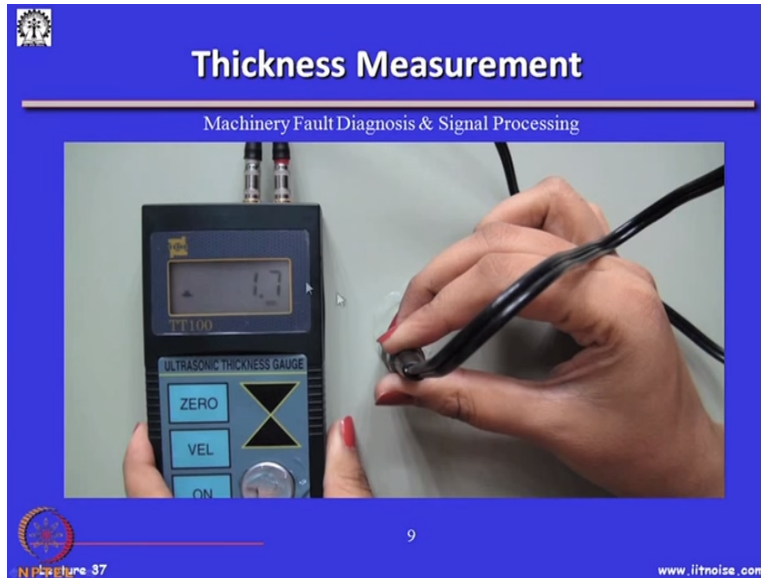
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So this is another example where in a thickness ultrasonic thickness probe is being used in the laboratory these are the thickness of the material this is actually a steel block and if you see here an this is about we have put the centimeter scale here about 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 about 100 centimeters and this is about 32MM approximation and this is maybe bearing 2 MM of the gap here which has been artificially created to explain to you or demonstrate you how this ultrasonic UT probe the red one is transmitter and the other one is the receiver built into this probe.

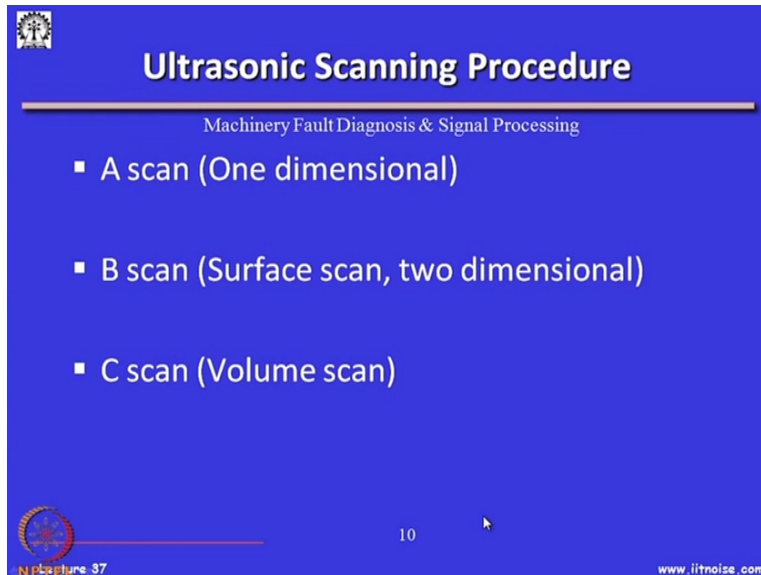
So this has been calibrated this is an ultrasonic thickness gauge this as been calibrated to measure the thickness of the steel by in this thickness gauge we have entered this speed of sound of ultrasonic wave in steel as 5000 meters per second and this is measured as 68 millimeter okay. So this can be used to measure the thickness and this device will behind this ultrasonic thickness gauge.

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Another one was this one a metal surface we would like to measure this thickness from outside so 1.7 if this is not possible to measure by a ruler or by a scale because you do not have a access to the other side of the material and you can see this should like gel I think that is the couplant we have put between the material and the ultrasonic probe to measure the thickness okay.

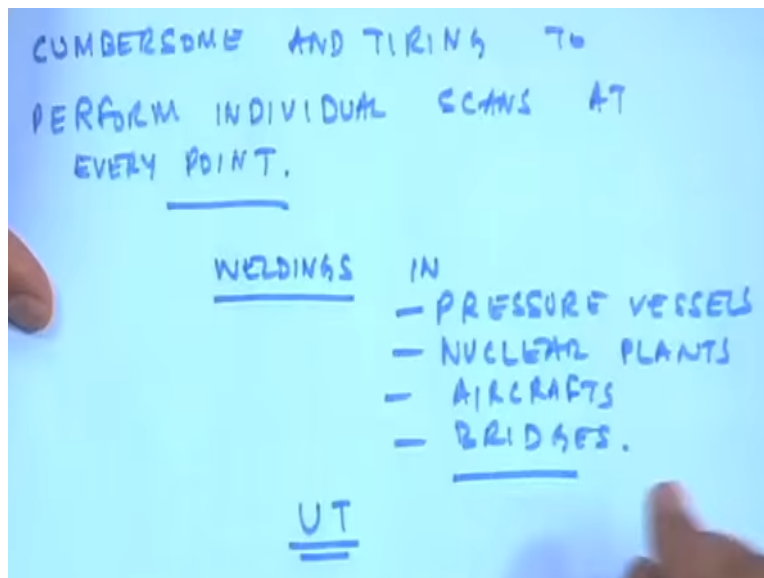
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So coming to the scan mode there are three scans A, B, C so A is the scan wherein at a single point I do a measurement B is actually a surface scan or say a linear scan quite not too dimensional. So if on the weldment I can get a B scan but then this is a this is a top view of a material okay. So this is an A scan at any point this could be a B scan okay and series of such B scans is actually represent as a C scan okay.

So these kind of scan images A scan, B scan, C scan so C scan gives us a contour of where the defect is and depend if there is a defect at a particular location this should come up as a change in the color intensity. So there is a lot of nice computer graphics in the software's which derive these ultrasonic systems where you can get a colored image of the entire surface okay. But you will notice that in such a scenario one as to anyway physically capture all the data at every A scan points and then put them together through a graphics.

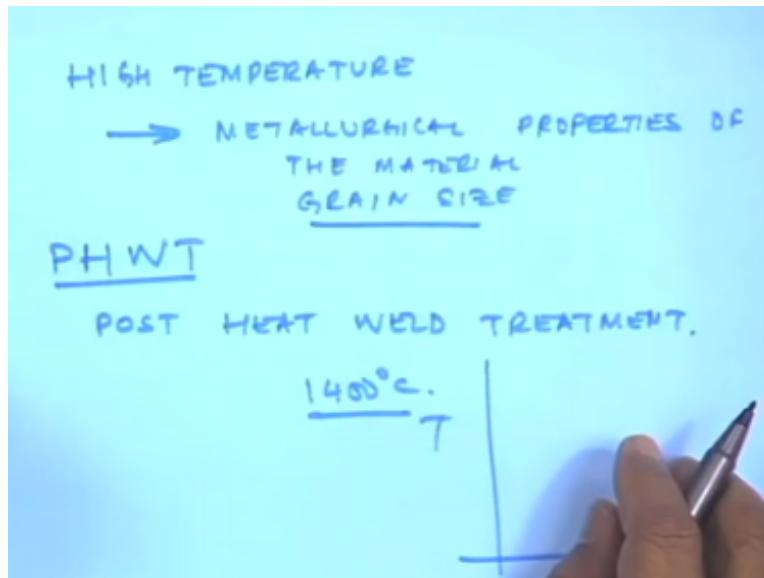
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So this becomes a little cumbersome and little tiring and tiring to perform individual scans at every point okay. So those I was telling you particularly for weldings in pressure vessels, nuclear plants, aircrafts, bridges okay they some of the codes they mandate that an ultrasonic scanning is done ultrasonic test is done to find out the weld defects. And this is the principle people use to do a find out the defects in welding because the whole problem welding.

Because if you would have seen in we will be studying a case study in many of the scenarios because welding brings about high temperature in the material.

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This changes the metallurgical properties of the material in terms of its grain size etc., So particularly in welding they do what is known as post heat weld treatment so because you know if you weld you go up to the melting point of the material and maybe around 14 degree and then if you cool with time the temperature the rate of cooling as lot of influence in the grain size which is developed in material.

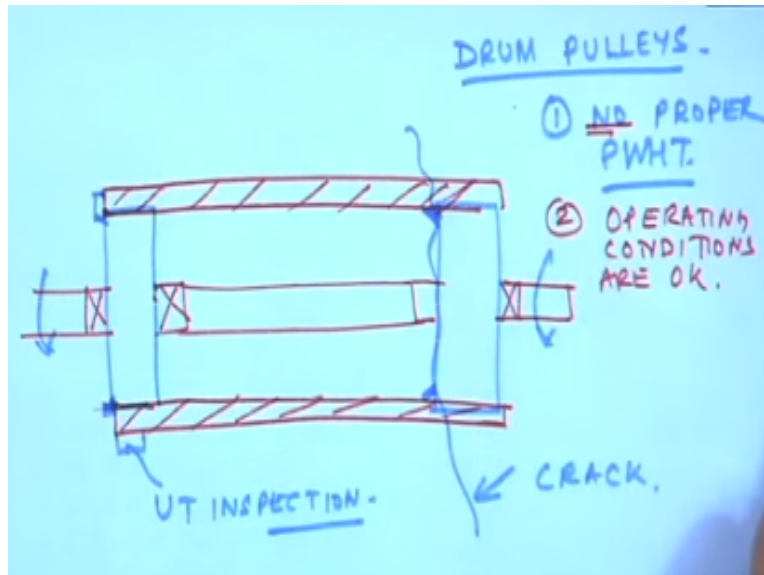
So sometimes the material can become brittle sometimes they can crack sometimes they become to brittle that they cannot sustain large fatigue loadings and they would fail so what happens usually after a post head weld treatment to ensure that there are no voids no cracks no defects it is mandatory in such critical applications in pressure vessels nuclear plants bridges etc they do a 100% ultrasonic test okay.

And it is only because of the this and this is the reason in many cases particularly in a draft etc you will see wherever possible people try to avoid a welding an maybe go for a riveting because of welding the most thing is that I could be changing the metallurgical composition of materials and when you see in condition based maintenance many time failures have occurred not because of the plant was not running within the limits everything was safe in terms of materials speed operational speeds and loads.

But because of an inherent material defect right in the manufacturing stage of a plant maybe a conveyor the system the brackets in the converse systems or the towers or the rails they broke

there have been cases where the conveyor the pulleys in a conveyor drive systems just sheared of because the way the pulleys are made I will show you one configuration of one right pulley.

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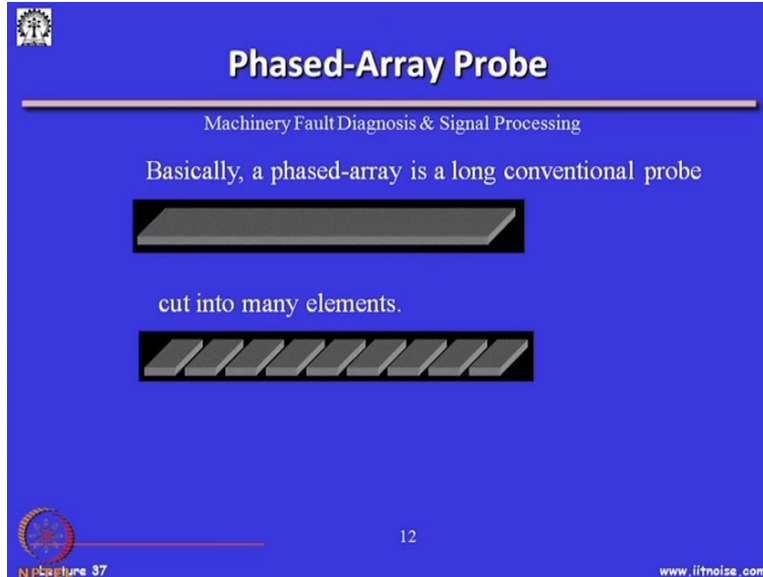


For example if you look at the pulley it is basically mirrored of two desks okay. Which is put at two ends and then there is a roll cylindrical roll and there is a shaft which is unfit as it is sometimes right here or sometimes it is through and through also and then if you and then there are bearings sorry okay so many times these areas welding is done this one area where welding is done okay.

There has been cases where we have seen that these materials fail in this crack occur in such pulleys they are known as drum pulleys okay. And this couple of reason because no proper post weld heat recovery treatment was done and so these kind of failures do not or not because of the operating condition the operating conditions are not good enough okay but because of no proper heat and such cases they recommend that an UT inspection is done.

I will report to a case study where we did do the metallurgical analysis of the failed structure and we could find out where there is difference in the Microstructure because of such harsh heat during a generator during welding okay.

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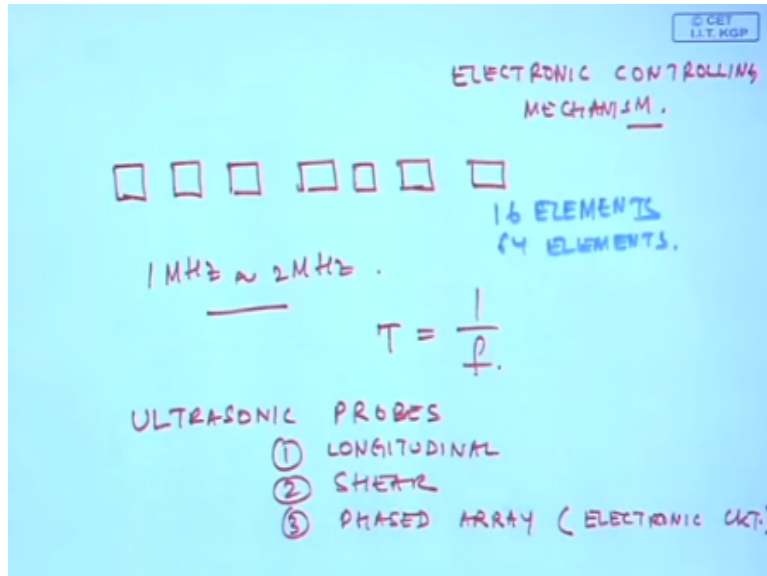


Now we will come to another technique because by now we have you must have realized that by ultrasonic I can have a probe generate a wave seats reflected intensity by some more measuring the reflected intensity we get couple of things one is the flight time duration which can be used to measure the thickness and if this thickness is because of the scale formation or because of the corrosion.

We can find out the change in thickness next is this ultrasonic probes can be used to find out internal defects like a void or a crack in a structure. But you must have realized if there is a bog structure and at every point if I have to do an ultrasonic scanning point by point this becomes a humongous task. So recently what has happened is basically a phased array probe is been made basically phased array probe which is cut into many piezoelectric elements like this.

And a phase that is in which the timing of the elements excitation can be individually controlled to produce desire surfaces are staring that beam axis are focusing the beam.

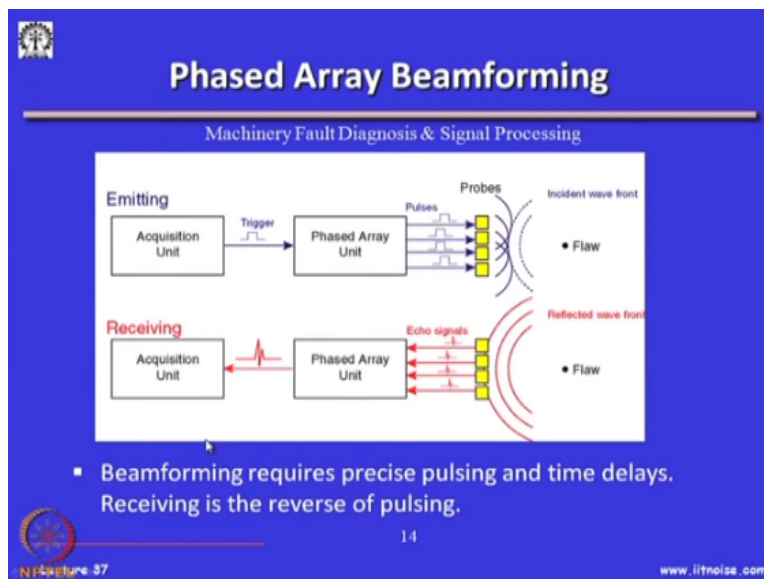
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So through an electronic timing of these phase arrays these preservative crystals they are equally spaced through so I can excite them in one go so all of them generate ultrasonic waves or I can excite this earlier than this so then the flight time will be different and then I can steer them or I can converge them so all this operations are possible through an electronic controlling mechanism or a circuit okay.

Now such structure I mean this could be held together maybe there are 16 elements usually probe are found in 16 elements or 64 elements. So imagine instead of one probe you have 16 probes 64 probes in one go okay. So for a quickly they can help you do the scanning.

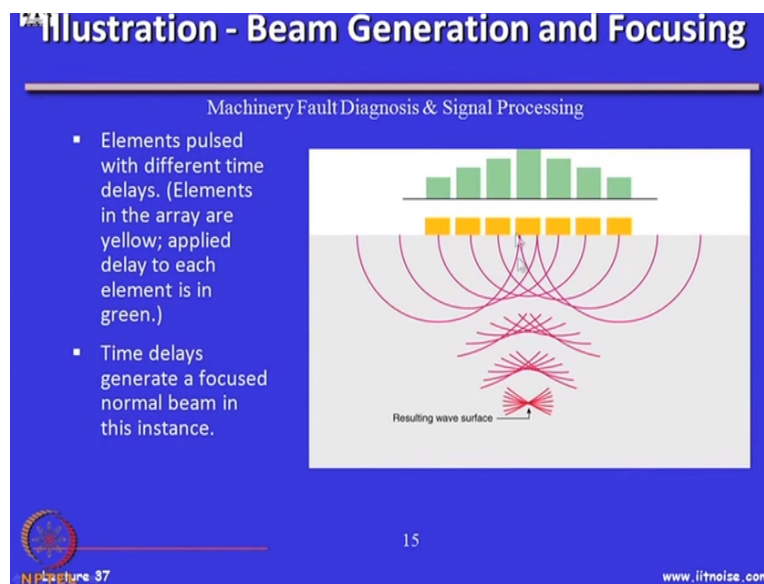
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So this is what is the phased array beam forming which happens so we have a acquisition unit okay. And then they will send the pulse and then we can get the there is a flaw and then there is internal because of the internal will come because of the reflection okay. And then depending on the phase delay or depending upon the intensity we can find out the defect location of the defect.

So but this require very precise pulsing and very precise estimating of calculating their time delays imagine you are talking about waves about 1 megahertz or to 2 megahertz. So this require very fast because the time delay know frequency time delay in inversely proportion to frequency the higher the frequency the time delay will be less and we have to be very careful or very fast processors to capture such signals okay.

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This is what is being used currently and this equipment we have in our lab okay and use this and this is just to show you how focusing can be done. Elements or pulse these are the elements with different time delays okay and these elements if more delays applied less delayed applied. So depending upon that they will focus on to the surface okay so these are all gimmickry of the electronic circuit which helps you generate a wave.

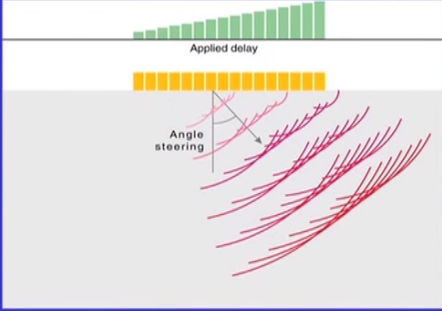
So I can focus it if I can steer it so all these scenarios are possible through such phased array processors.

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Illustration - Beam Deflection

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- For shear waves, the time delay pattern has a “slant” as shown here.
- Focusing can be performed by adding “parabolic” time delays to the slant.



16

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There is another example for shear waves because sheering have to slant it so I have to steer it. So I can again generate increasing time delay and then I can generate a steer way. So this angle can be change by the delay and that is the beauty of such array probes okay. So this ultrasonic probes are available in many forms one is the longitudinal probe other is the sheer wave probe.

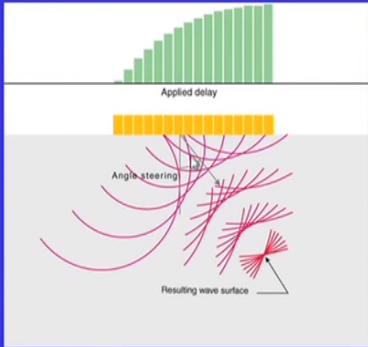
Sheer wave probe is actually angler and then we have the phased array, phased array probe is actually many such ultrasonic probes held together and through electronic circuit. We can generate okay and sometimes the transmitter and the receiver held together in one unit.

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Illustration - Beam Deflection and Focusing

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- Beams generated in very early stage, mid-stage, late stage and at focus.



17

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So beams could be again used to focus they will all converge and finally focus.

(Refer Slide Time: 48:21)

Beam Steering

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- Is the **capability to modify the refracted angle** of the beam generated by the array probe.
- Allows for **multiple angle inspections**, using a single probe
- Applies asymmetrical (e.g. linear) focal laws

18

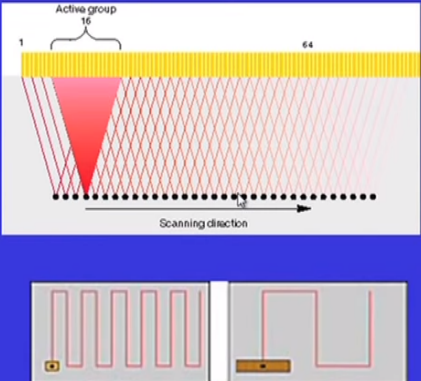
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So in this this are all this are the phase are the green ones are the phased arrays but you can see by changing the control circuit many configuration are possible beam steering straight incline as symmetrical and so on can be done and then this will help you to find out the flaws.

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Electronic (Linear) Scanning

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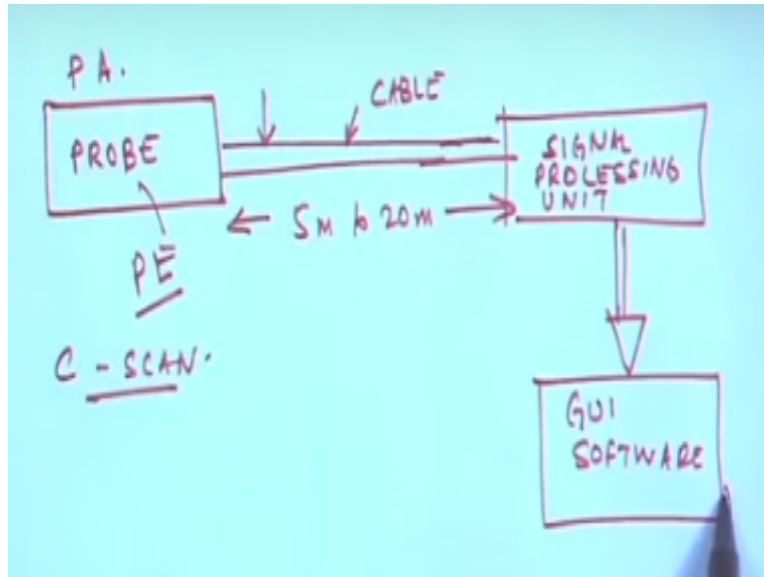
19

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Another is this linear scanning okay this is what I was talking about there are certain active group is 64 element probe and then you can scan then and then scanning method could be like this you can probe them. So the entire surface can be scan and then you can get the intensity of these waves wherever there is a defect the intensity is going to change. So you can get an image of C scan of the ultrasonic test and this is how it can be done okay.

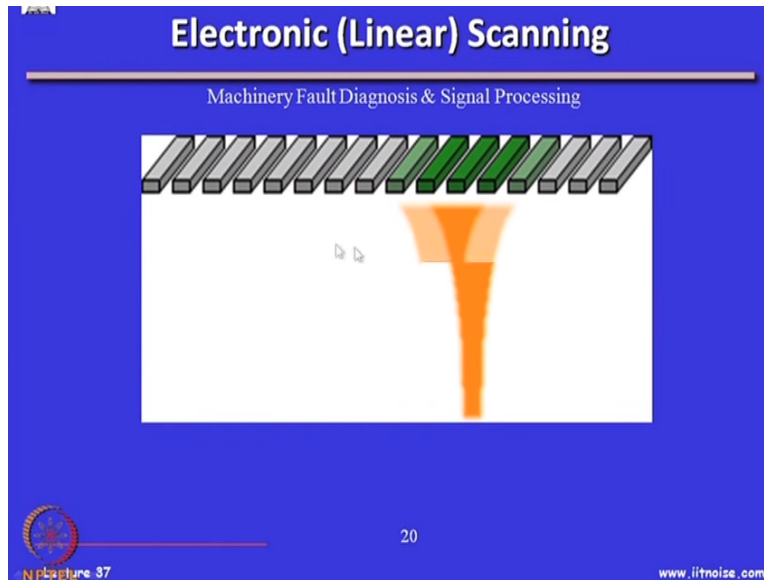
And all you to do is hold the probe and the traverse it and there are 16 active elements okay into the probe. And lot have to be done with the cable because sometimes these cables in this probes are also equally costlier okay.

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So this is a probe and then we have a cable and the signal processing unit of course this interface with a good UI based software sometime care as to be taken care because it all piezoelectric materials this cables you know typically in a plant you know this is about this has come in standard event from 5 to 20 meters okay. So this could be traversing the probe depending on which ever scan mode and usually easily scan can be done with such faced array probe okay.

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And then you get a GUI software where you can get the image of the system so this is one method by which the linear scanning is done you can see the graphics okay one by one. So this is just by moving the electronic signals stimulus physically the probe as not moved. Probe has stayed on the entire surface but just moving the electronic energizing particular element my wave are being generated.

(Refer Slide Time: 51:17)

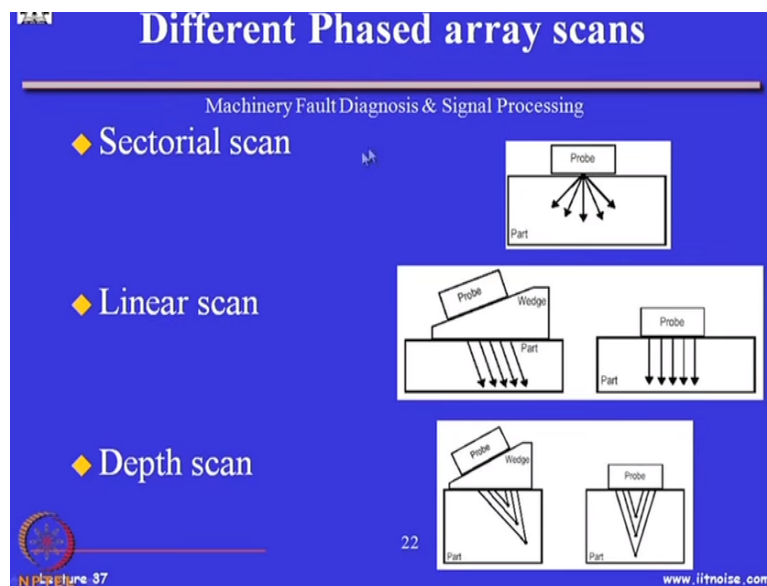
- Is the **ability to move the acoustic beam** along the axis of the array without any mechanical movement.
- The beam movement is performed by time multiplexing of the active elements
- Scanning extent limited by :
 - number of elements in array
 - number of “channels” in acquisition system

So you can scan them accordingly so this is what is known as the electronic scanning a linear it is ability to move the supposed to be along the axis of the array without any mechanical movement okay. The beam movement is performed by time multiplexing of the active elements

scanning extent limited by number of elements in the array number of channels in the acquisition systems.

Because this is the multi-channel acquisition system so this as I was telling instrumentation as come a long way to help the ultrasonic in particularly condition based maintenance and recently earlier we used to have just single elements ultrasonic probes having resonance facility crystals having a resonating structures but now a days such electronic linear scanning we can produce beams and we do the scanning almost immediately.

(Refer Slide Time: 52:17)



So these are the some of the views of the phased array scans so these are the sectorial scan this is linear scan I am sorry okay and then we have a linear scan and then this is a combination of the scan how they are arranged in the probe different elements.

(Refer Slide Time: 53:02)

Combined Beam Processing

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24

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And then this can be scanning so all along the edges you know this suppose this is the well meant you can do the scanning in final.

(Refer Slide Time: 53:13)

Why Phased Array?

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- High speed electronic scanning without moving parts
- Improved inspection capabilities through software control of beam characteristics
- Inspection with multiple angles with single, electronically controlled probe
- Greater flexibility for inspection of complex geometries
 - Optimized focusing
 - Optimized beam angle

25

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So the advantage of phased array ultrasonic ultrasound scanning is high speed electronic scanning without moving parts improved inspection capabilities through software control of beam characteristics inspection with multiple angles with single electronically controlled probe and get a flexibility for a inspection of complex geometries and so on okay.

(Refer Slide Time: 53:35)



OMNISCAN PHASED ARRAY

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NP 37

26

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This is one such phased array system we have you know in our laboratory wherein you can get an image of the area where you are scanning very similar to the doctors ultrasound monogram which would have seen so you can see a defect according to here in a C scan. So ultrasound has become very popular because of this software's which are available and because of the advantage in phased array electronic systems which can be used for doing a quick scan of systems and finding out defects thank you.